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Title: Complex Dark Matter

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For those who study the cosmos, it is not unusual to encounter objects of great beauty, ranging from the magnificent rings of Saturn, to the elegant Crab Nebula, a remnant of an 11th century supernova. However, there are few astronomical denizens as majestic as a spiral galaxy. An example is the nearby Andromeda Galaxy, an enormous cosmic pinwheel consisting of a trillion stars and destined to collide with our own Milky Way in just shy of four billion years. While there is no controversy on these facts, there is one glaring problem.

The Andromeda Galaxy shouldn't exist.

The breakneck speed of its rotation is in conflict with the known laws of physics applied to the observed matter. The stars in the periphery are moving too fast to be held in the galaxy by the gravity generated by ordinary matter. By all rights, Andromeda …indeed nearly all galaxies …shouldn't exist with the rotational properties we observe.

The observation that galaxies rotate too fast has led to a variety of possible explanations, ranging from modified theories of gravity and inertia, to the existence of unseen matter surrounding and permeating them. Over the years, many of the various ideas have been put to the test and the explanation that has best survived the winnowing process is the existence of a new type of particle that forms *dark matter.*

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Dark matter is invisible to light and the mass of dark matter in any galaxy usually exceeds the mass of ordinary matter and must be distributed over a spherical and much larger volume.

The hypothesis of dark matter explains many additional astronomical mysteries, including the exceedingly fast motion of galaxies within clusters of galaxies, the distribution of matter arising when two clusters collide, and the observation of gravitational lensing of extremely distant sources of light. Agreement with data requires the dark matter particles to be moving slowly compared to the speed of light; borrowing terminology from thermodynamics, dark matter must be “cold”.

Properties of dark matter particles

While dark matter has not been directly observed, to be consistent with observations, the dark matter particle has some specific properties. To begin with, it must be electrically neutral. If it weren’t, it would interact with light and we would see it. The particle must interact gravitationally but does not interact electromagnetically or via the strong nuclear force. It could experience interactions mediated by the weak nuclear force, but only together with other new particles; it could also interact with the recently discovered Higgs particle. Undiscovered forces may also come into play – until the dark matter question is settled, scientists remain open to all options allowed by data.

Scientists use a broad range of search techniques, from laboratory attempts to directly detect dark matter passing through the Earth, to satellite measurements of cosmic rays that may originate from dark matter annihilation in parts of the cosmos in which it is thought that dark matter concentration is high. So far, none of these measurements has found convincing evidence for a dark matter particle.

Nevertheless, the compelling astronomical and cosmological evidence provides additional clues. The first clue is that dark matter is stable on cosmic timescales. That simple statement hides a profound truth, specifically that the dark matter particle has a property that is “conserved” and thereby forbids it to decay.

A familiar conserved property is electric charge, which ensures that the electron is stable. It is a truism of physics that particles decay into lighter ones unless the decay is forbidden. The electron is electrically charged and the only known stable particles lighter than it are electrically neutral: the photon and the neutrinos. Energy considerations would allow the electron to decay into these objects, but charge conservation forbids such decays.

Theories that include a dark matter particle typically employ a conserved quantity called “parity,” with the dark matter particle having a parity of -1 and all the particles discovered so far having a parity of +1. The decays of the dark matter particle into ordinary matter are then forbidden by this parity because if the dark matter particle disappeared and ordinary particles appeared, the parity would change and thus not be conserved.

A second clue is provided by cosmological evidence. Using measurements of the cosmic microwave background, astronomers believe that the total amount of dark matter in the universe is a little over five times heavier than all ordinary matter. This abundance imposes an important restriction on the properties of the dark matter particle. The most studied scenario is that where the dark matter particles have some interactions besides gravitational so that they were in thermal equilibrium during the early universe. The dark matter particle in this scenario is referred to as WIMP, for Weakly Interacting Massive Particle. The term “weakly” here is used in the generic sense, not necessarily for the weak nuclear force.

According to the prevailing theory, at very early times, the WIMPs were continuously produced and annihilated due to the huge temperature of the universe. Once the universe cooled enough so that WIMP production became unlikely, the dark matter abundance has been determined by the probability for WIMPs to meet and annihilate. That rate turns out to be similar to the rate of processes involving the weak interactions. This coincidence, dubbed the WIMP miracle, suggests that the dark matter particle is pointlike and has a mass roughly between one and ten thousand times the proton mass.

In the paradigm described above, WIMPs are their own antimatter particle, implying that they annihilate whenever they meet. In other models, matter and antimatter WIMPs are distinct, so that a matter WIMP can annihilate only when it gets close to an antimatter WIMP. We see in regular matter an overwhelming asymmetry between the observed matter and antimatter. This asymmetry is thought to have originated in a tiny asymmetry early in the history of the universe in which for each billion antimatter particles, there existed (approximately) a billion and one matter particles. The billion matter and antimatter pairs annihilated, leaving the residual matter particle to form the observed matter of the universe. It is likewise possible in the dark matter sector that such an asymmetry exists, in which case the dark matter in the universe may clump without annihilating. This idea is called “asymmetric dark matter.”

Complex dark matter?

Despite the remarkable successes of cold dark matter in solving astronomical puzzles, some residual mysteries might persist. One of them is called the “missing satellites problem.” Computer simulations show that around large galaxies like the Milky Way and Andromeda there should be a significant number of dwarf galaxies, each consisting of as many as a few billion stars (in contrast to the Milky Way’s 200 – 400 billion stars). Approximately twenty dwarf galaxies have been observed around the Milky Way, while some simulations predict that there should be as many as 500. In addition, simulations indicate that dwarf galaxies should be distributed approximately uniformly around the Milky Way, while the observed locations tend to be in in a plane that is perpendicular to the orbital plane of the galaxy. Another problem is that simulations of the dark matter distribution predict a too high concentration at the center of galaxies to be consistent with the observed rotation curves. While these simulations are not conclusive (for instance, there is no consensus yet of how to include the effects of ordinary matter), these unexplained observations have led scientists to consider possible tweaks to the WIMP model.

A modification that appears to reconcile all of the observations and simulations is the inclusion of a strongly coupled dark matter self-interaction. Combined with the asymmetric dark matter paradigm, this self-interaction suggests that dark matter may be quite complicated.

To understand the basic idea, we only have to look at the familiar kind of matter that we encounter on a daily basis. We are made of atoms that are ultimately composed of quarks and electrons. Five known interactions govern the behavior of matter: gravity, electromagnetism, the strong and weak nuclear forces and the force mediated by the Higgs boson. Matter makes up molecules, planets and stars. Ordinary matter is really quite complex.

In contrast, traditional WIMPs are imagined to be simple: a single type of neutral and massive particle that interacts gravitationally and possibly via other weak forces. But what if it isn’t so? Over the last few years, scientists have increasingly proposed that maybe there are several varieties of dark matter and, perhaps even more intriguing, that there exist new forces that act strongly on dark matter and very feebly or not at all on ordinary matter. For example, dark matter could consist of particles that carry a charge that exerts a force between them, while being electrically neutral. Just like ordinary particles with electric charge can emit photons, perhaps particles with dark charge could emit “dark photons”. And the idea doesn’t stop there. One could imagine that there exist several classes of dark matter particles and a variety of forces that only dark matter particles feel. Dark matter could be as varied as ordinary matter.

This idea is clearly speculative and is partially motivated by the suspicion that perhaps the dark sector exhibits some of the features of ordinary matter. Complex dark matter also has the virtue that it can reconcile some of the problems of the single-WIMP models, although it will be impossible to nail down a definitive theory without more data. It is important to realize that while there is much that we don’t know about dark matter, we know enough to constrain various speculations. For instance, we know that the world of complex dark matter cannot be identical to our familiar world.

The reason we can say that is the following. Suppose that the rules of the dark world exactly mirrored ours. In that world, dark atoms would be formed and would emit dark photons. In our world, the emission of photons allows energy to be lost and exchanged and is the reason why galaxies eventually relax into disk-like objects. Clouds of gas radiate electromagnetic energy which results in the matter that makes up the clouds being attracted together. Conservation of angular momentum forbids the matter to contract to a point, but a disk-like structure forms easily.

If the rules and forces governing the behavior of dark matter were the same as ours, the emission of dark photons would result in similar dark matter disks. Yet we know that the distribution of dark matter required to explain our familiar galaxies is more like a spherical cloud. Thus we can rule out an exact mirror world of dark matter.

Still, there remain many options. For instance, it is possible that a small fraction of the dark matter mirrors the rules of our universe, while the larger fraction acts more like the simple WIMPs. Or perhaps the dark charge is effectively much lower than the electric charge of our electrons and protons, resulting in reduced dark photon emission. Scientists are generating many ideas as to possible particles and forces of the dark sector, using existing data to guide their thinking and to constrain their speculations. To give a glimpse as to the process, let us describe one of the simpler models of complex dark matter.

Dark Photons

So let's think about a dark world in which there exists two kinds of dark charge $Q_{dark} = \pm 1$. In this theory, there is a form of dark electromagnetism, leading the dark matter particles to emit and absorb dark photons. Since we have postulated that these particles are charged in a way analogous to ordinary electromagnetism, positively- and negatively-charged dark matter particles should be able to meet and annihilate into dark photons. What can astronomical observations tell us about this possible theory of dark matter?

There are two parameters that determine the annihilation probability of charged pairs of particles like this. The first is the strength of the dark force. If the force between two objects has a large strength, the objects will attract each other and are therefore more likely to annihilate. The other parameter is the particle density, which is related to the probability that two oppositely-charged particles encounter one another. If two particles are separated by a very large distance, the chance they will cross paths is very low. Given that both of these factors come into play, any limits we can set on them will be interrelated. However we can sketch out some of the basics.

Astronomical measurements tell us that there is about five times more mass in dark matter than in ordinary matter. If a dark matter particle is, let's say, about a hundred times heavier than the proton, then it is straightforward to calculate the dark matter density. It turns out that there is about one dark matter particle in every fist-sized volume of space. In order to allow this dark matter density, the strength of the dark force must be smaller than the strength of electromagnetism, given by the fine structure constant $\alpha = 1/137$.

The above constraint that dark matter doesn't annihilate too much is useful, but it turns out that there is an even stronger constraint. Dark electromagnetism, like its ordinary counterpart, is a force with a range. Recall that the reason that galaxies have a disk like structure originates in the fact that electromagnetism allows ordinary matter to lose energy and to settle in the disk configuration. This occurs even without annihilation.

Since we know that dark matter is mostly diffuse, it follows that it cannot lose energy via dark photon emission at the same rate that ordinary matter does. L. Ackerman et al have shown that this requirement implies that the dark force must be substantially weaker in this model, approximately $\alpha_{dark} < 10^{-4}$.

Two component dark matter

So far, we have described three types of possible dark matter: the simple WIMP, asymmetric dark matter, and a version of symmetric dark matter consisting of a matter/antimatter pair carrying dark charge and emitting dark photons. However, these models pale in comparison to the complexity of ordinary matter. Maybe dark matter consists of two or more classes. What would that look like?

An example of how these ideas may be combined was proposed in 2013 by Fan, Katz, Randall and Reece, who referred to their model as Partially Interacting Dark Matter. The bulk of dark matter was taken to be a WIMP. However their model also postulated that a small component of dark matter consisted of two classes of fermions: one heavy and one light, both of which carried dark charge. Because the particles carry dark charge, they emit dark photons and can be attracted to one another. While one must be very cautious to not over-interpret the correspondence, the proposed situation is broadly similar to postulating a dark proton, a dark electron, and a dark photon to bind them together. Depending on the mass and charges of the fermions experiencing dark charge, it is possible to imagine dark atoms, molecules and possibly even more complex structures.

They went on to derive an upper limit on the fraction of dark matter that may be strongly interacting with the dark photon, and determined its mass may be as large as that of all visible matter. In this model, the Milky Way galaxy consists of a large spherical cloud of 70% WIMP-like matter and two disks, each containing 15% of the matter: one disk consists of familiar matter and one consists of strongly interacting dark matter. The two disks need not be exactly aligned, but should have a similar orientation. It is possible to imagine something akin to a dark matter galaxy coexisting in the same space as our familiar Milky Way. A cautionary note: the dark matter galaxy would not include dark stars or large planets, as these would have been observed by experiments searching for gravitational lensing effects of ordinary matter rogue planets, black holes, brown dwarfs and burned out stars.

Experimental prospects

Direct searches for complex dark matter can be similarly to WIMP searches. Using a vast array of technologies, researchers build detectors that may capture the extremely weak interactions of dark matter with ordinary matter. To achieve the necessary sensitivity, the detectors are cooled to very low temperatures and the detectors are located deep underground to shield them from ubiquitous cosmic rays, which can mimic a dark matter signature. One consequence of the partially interacting dark matter, with its concentrated disk of matter roughly in the same plane as the visible matter of the Milky Way, is that this form of dark matter passing through our detectors would be denser than that predicted in WIMP models. This increased density could result in a greater probability to discover dark matter.

While an extensive experimental program exists to look for naturally-occurring dark matter, physicists also hope to make dark matter in particle accelerators. Because we know very little about how dark matter interacts with ordinary matter, scientists have embarked on a broad program of investigation. Ideally this program will be sensitive to a variety of models of dark matter, ranging from the simple WIMP to a more complex dark sector, although there are a few necessary assumptions to pursue this avenue of investigation. To begin with, we must assume that dark matter interacts with ordinary matter via a force or forces that is much stronger than gravity and weak enough to not yet have been observed.

The CERN Large Hadron Collider is the world's highest energy accelerator, which gives it an edge when searching for heavier versions of dark matter, as well as for dark matter particles whose interactions grow with the energy. Because dark matter doesn't interact very much with ordinary matter, it isn't observed in the detector. Instead, scientists search for dark matter production by looking for collisions in which energy is missing. Two protons collide and produce some ordinary particle to one side and a couple of dark matter particles to the other. The signature is observed energy on one side of the detector with nothing on the other side. Scientists calculate how many collisions are expected to have this striking configuration and look to see if there are more than expected. If there are, this could well be the signature of dark matter being created at the LHC. Using the ATLAS and CMS detectors at the LHC, physicists have set limits on the strength of interactions between dark matter particles and ordinary particles. The sensitivity of these searches is expected to increase substantially when the LHC resumes operations in 2015.

While the approach we just described is suitable for searches for both WIMP and complex dark matter, there are approaches that are more specifically aimed at the complex dark sector. Many of these search for the dark photon. There are models in which dark photons can constantly oscillate into ordinary photons and back again, and others in which there are dark photons which have a non-zero mass. (The use of word “photon” is stretched in that case.) Since ordinary photons interact with regular matter, they can convert into pairs of leptons. Consequently, scientist search for collisions in which an electron/positron or muon/antimuon pair are produced. Studies like this are being pursued at the LHC, but also at KLOE-2 experiment at the INFN Frascati National Laboratory in Italy, at the Heavy Photon Search (HPS) experiment at the Thomas Jefferson National Accelerator Facility in Virginia, the BaBar detector at the Stanford Linear Accelerator Center (SLAC) and even by digging through decade-old data taken by the SLAC mQ experiment.

Another interesting approach utilizes the Fermilab accelerator complex to try to make beams of dark matter particles. Fermilab is currently generating intense beams of neutrinos that it is shooting at distant detectors. If dark matter interacts with ordinary matter via some particles like dark photons, it is possible that dark matter is being made in the same beams and can possibly be detected in the MiniBoone, MINOS or NOVA detectors. Physicists have recently started to study the data being collected to see if there are any surprises that could indicate that complex dark matter is being made.

Concluding remarks

There is no question that there is a mystery in the universe. Matter doesn't act in ways consistent with the known laws of physics and the observed mass distribution. Because of this, most scientists are confident about the existence of a very weakly interacting particle that forms dark matter. However, that particle has still not been detected after decades of searches. Furthermore, some tension may exist between the simplest WIMP model and certain astronomical observations. This has led some physicists to modify the particle model of dark matter to include more complex interactions, which give more knobs to improve agreement between data and theory.

A criticism of this approach may be that it works overly hard to keep the dark matter hypothesis alive. Could this be similar to the discredited idea of epicycles, whereby 16^{th} century astronomers tried to retain geocentrism by adding a constant series of tweaks to a fatally-flawed theory? That does not seem to be the case given that the idea of dark matter explains remarkably well many astronomical conundrums, and there is no reason a priori why dark matter should be as simple as the WIMP hypothesis.

Taking our lessons from ordinary matter, it is plausible that dark matter has a rich and complex nature. The real message is that we have a mystery before us and we don't know what the answer will be. Until then, we must be open to various explanations, including the fascinating possibility that we might be living along a dark parallel reality. Could it be that a dark matter scientist has turned its attention to its skies and is wondering about us?

Further Reading

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Figure options: